

# **Internal Tides and Solitary Waves in the Northern South China Sea: A Nonhydrostatic Numerical Investigation**

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Award Number: N00014-05-1-0279 (UMCES)  
Award Number: N00014-05-1-0280 (NCSU)

## **LONG-TERM GOALS**

The goal of this project is to understand processes relevant to the generation, propagation and dissipation of finite-amplitude internal solitary waves observed in the region from the Luzon Strait to the Chinese continental shelf.

## **OBJECTIVES**

With data available from field observations in Non-Linear Internal Wave Initiative (NLIWI), this project is to perform simulation of finite-amplitude internal solitary waves under realistic scenarios in the northern South China Sea. The objective is to provide information on the characteristics of nonlinear internal waves for comparison with data collected from remote sensing, mooring measurements, and shipboard observations.

## **APPROACH**

Processes of wave generation, propagation and dissipation are studied by numerical simulation using a nonhydrostatic ocean model under different scenarios of bottom topography and stratification. Experiments include wave generation by ridges in the Luzon Strait and by density fronts, wave propagation across the deep basin with a shoaling thermocline, wave reflection and diffraction near the Dongsha Island, wave generation and dissipation on the continental slope, and characteristics of higher-mode waves.

## **WORK COMPLETED**

Work in the following three categories has been completed in the past year.

- 1) Wave transformation on the continental shelf

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE <b>30 SEP 2007</b>		2. REPORT TYPE <b>Annual</b>		3. DATES COVERED <b>00-00-2007 to 00-00-2007</b>	
4. TITLE AND SUBTITLE <b>Internal Tides and Solitary Waves in the Northern South China Sea: A Nonhydrostatic Numerical Investigation</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Horn Point Laboratory, UMCES,P.O. Box 775,Cambridge,MD,21613</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>code 1 only</b>					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>8</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

Continuing the previous work of reflection and diffraction by a circular island at the shelf edge, we have studied the transform of solitary waves impinging on the continental shelf.

## 2) Source(s) of internal solitary waves:

The source region of the internal solitary waves in the Luzon Strait has been modeled. Continuing on the effects on the wave generation and damping, we have studied the vertical propagation of internal waves from the ridge top and its subsequent development into internal solitary waves.

## 3) Tides and currents in Taiwan Strait and in the Kuroshio

We have collaborated with PIs in Taiwan on the analysis of tides and currents obtained from regional numerical simulation in the Taiwan Strait and in the vicinity of the Kuroshio. The results are reported in papers in the publication list.

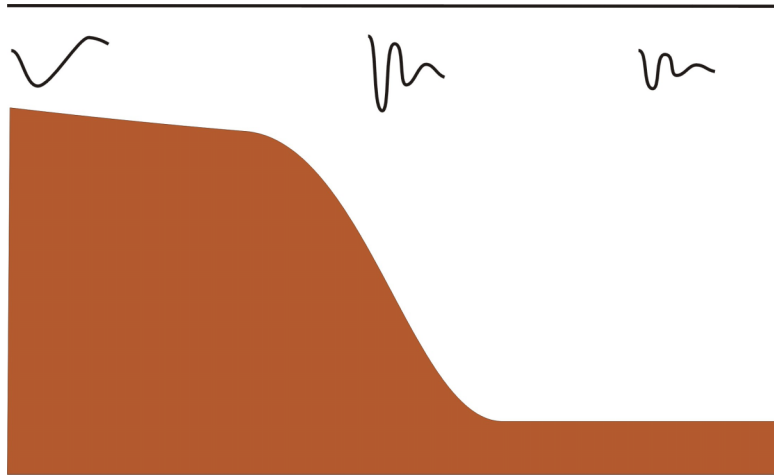
# RESULTS

## 1) Wave transformation on the continental shelf

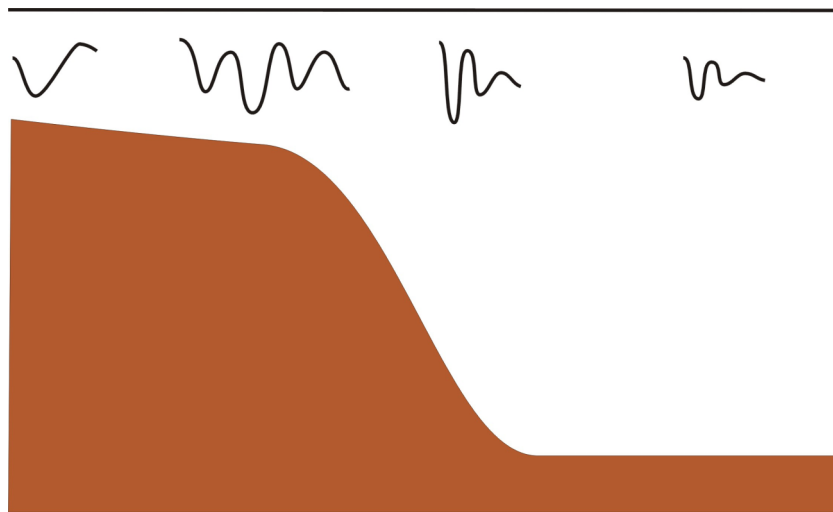
The question we want to address is “As a solitary wave continues to move shoreward, how many types of wave can it transform into?”

To address the issue, we use body forcing to generate internal tides near the eastern boundary of the domain. Internal solitary waves evolve from the internal tides and propagate onto the shelf. The solitary wave is first amplified by the shoaling bottom on the slope as shown in Figure 1. After reaching the shallow shelf, the wave evolves to a broader depression wave. This smooth transition is for a modest incoming solitary wave. For a strong incoming wave, trailing oscillations may appear behind the wave front as the wave propagates onto the shelf (Figure 2). A snap shot of the trailing oscillation is shown in Figure 3. Multiple wave crests trailing a wave front on shelf are frequently seen in satellite observations. The presence of trailing oscillations is independent of the thermocline depth. For a deep thermocline, the wave transforms to a broad elevation wave with similar trailing oscillations.

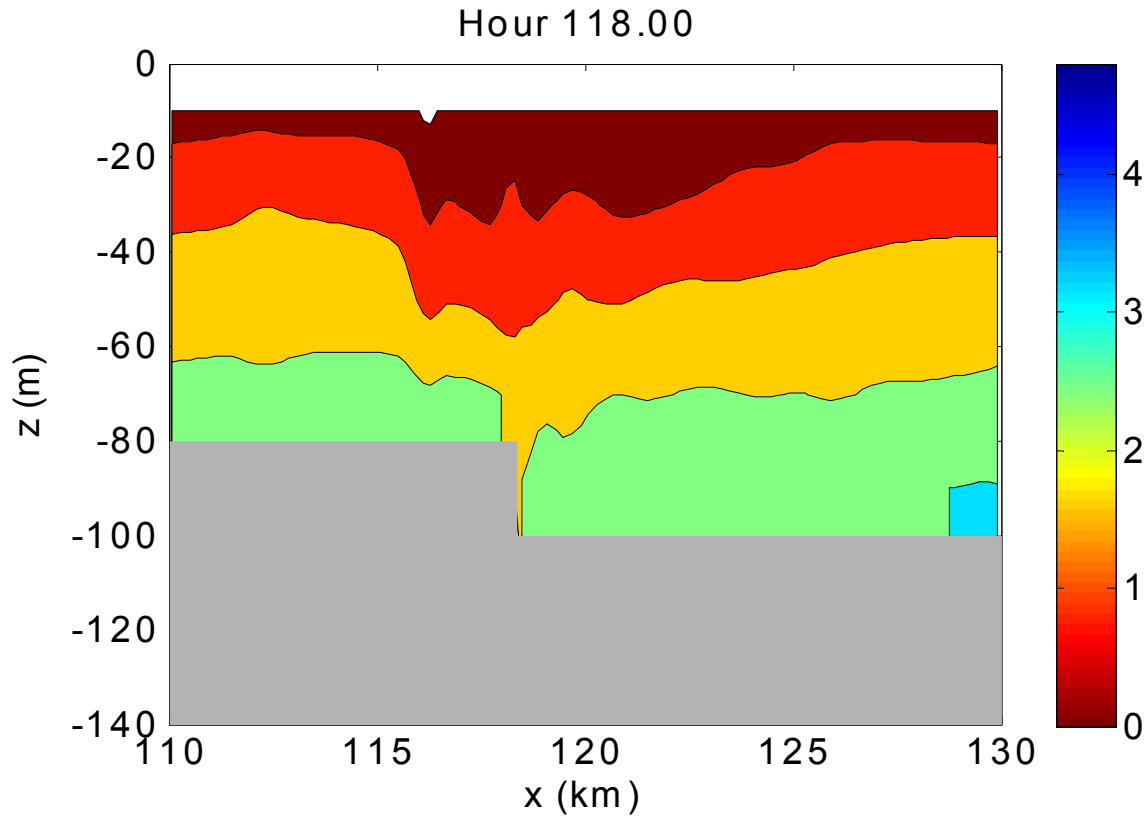
Other features shown in our simulation include attrition of the wave on shelf by bottom form drag and the development of an along-isobath current by earth’s rotation.



*Figure 1. Transformation of an internal solitary wave packet to a broad depression on shelf.*



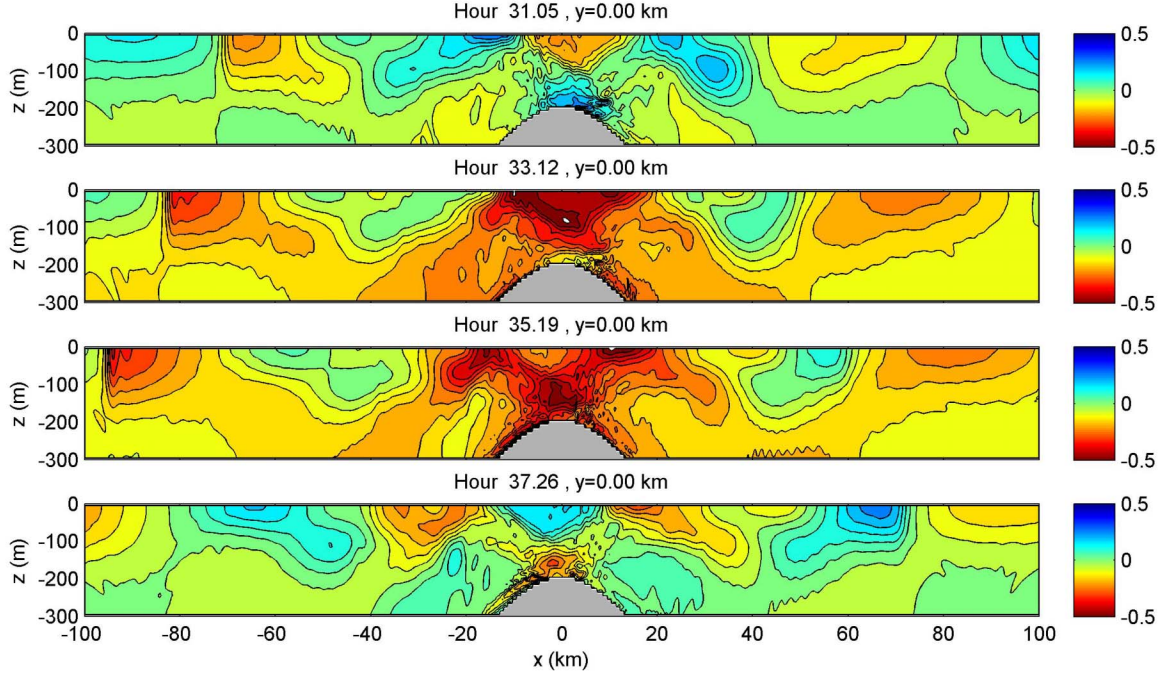
*Figure 2. Transformation of a strong internal wave packet to a broad depression on shelf.  
[Trailing oscillations appear behind the wave front.]*



***Figure 3. Development of trailing oscillations on shelf for a strong incoming solitary wave packet.***

## 2) Source(s) of internal solitary waves:

Progress has been made to the generation of internal solitary waves. Our emphasis is on the generation of vertically propagating internal tides at the tip of the ridge. In a plot of the horizontal velocity in the  $x$  direction (Figure 4), vertically propagating internal waves at the ridge are clearly shown. The waves emit from the lee side of the ridge toward the surface. Subsequent reflection by the surface and refraction produce first-mode waves, which intensify to form solitary waves. In the second panel of Figure 4, the first-mode internal tide, originating from the ridge in the previous tidal cycle, is developing into a solitary wave packet near  $x = -80$  km.



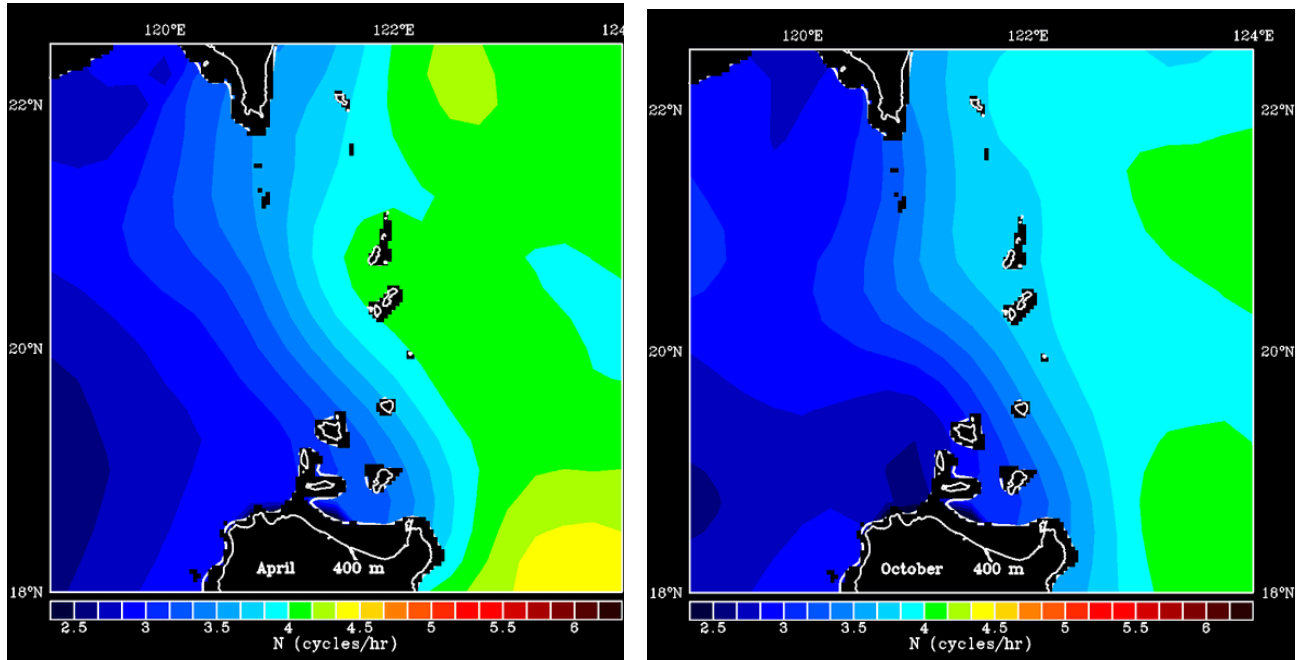
**Figure 4. Generation of vertically propagating internal waves at the top of a ridge. The contour interval is 0.05 m/s.**

A summary of the cases we have studied is shown in Table 1. Experiment 0 is the one shown in Figure 4. Drastic changes in behavior occur when the width of the ridge is doubled (Experiment 1). The internal solitary waves are not generated. In this case, the downward energy propagation is blocked by the ridge. Internal solitary waves are not present even when the forcing is doubled (Experiment 2). For weaker stratification (Experiment 3), the wave rays are more vertical, and internal solitary waves are not generated. However, if the ridge is narrower, internal solitary waves again are possible (Experiment 4). For diurnal tides, the wave rays are more horizontal than those of the semidiurnal tides. Internal solitary waves can be generated over a less steep ridge (Experiment 5) if the barotropic tides are strong enough to compensate the spreading of energy over a longer wavelength than in Experiment 0. Note that the tidal velocity is subcritical in all these experiments. The generation mechanism is therefore strongly dependent on the angle of the wave beams. It seems that the generation of internal solitary waves requires the bottom slope at the upper part of the ridge to be greater than  $\tan(\alpha)$ , where  $\alpha$  is the angle between the wave beam and the vertical axis. We conclude that a steep ridge, stronger stratification, and a longer forcing period favor the generation of internal tides and thus internal solitary waves.

A preliminary test of the above hypothesis has been made. Figure 5, provided by Dong-Shan Ko, shows plots of climatological distribution of buoyancy frequency ( $N$ ) at 400 m in the Luzon Strait from numerical simulation. The closed solid line is the 800 m isobath showing the East Ridge. In April a band of water with high  $N$  values near the ridge favors the generation of solitary waves. In October, water with low buoyancy frequency moves over the ridge, producing a less favorable condition for generating solitary waves. According to our hypothesis, these patterns of buoyancy frequency may explain the higher number of solitary waves observed in spring than in the fall.

**Table 1. Experiments on internal tide generation**

Experiment	Ridge width (km)	Tidal velocity (m/s)	Buoyancy frequency	ISW?
0	30	0.1	N	yes
1	60	0.1	N	no
2	60	0.2	N	no
3	30	0.1	N/2	no
4	15	0.1	N/2	yes
5	60	0.2	N	yes



**Figure 5. Distribution of buoyancy frequency at 400 m in April (left panel) and October (right panel) from Dong-Shan Ko.**

## IMPACT/APPLICATIONS

The wave generation hypothesis can be tested in observations. Steep-sided ridges and strong stratification near the ridge top favor the generation of internal solitary waves. We are using Steve Ramp's mooring observations on top of the ridge in the Luzon Strait to verify our hypothesis. We are also collaborating with Dong-Shan Ko to look into the generation mechanism based on climatology in the Luzon Strait. We hope to develop a criterion for the wave generation in the Luzon Strait. This study can further be extended to other parts of the world ocean.

## **RELATED PROJECTS**

We plan to use Steve Ramp's data in the analysis. In addition, we have been using the oceanic conditions from Dong-Shan Ko's climatological simulation extensively. We have also worked with S. Jan and C.-R. Wu on the circulation in the Taiwan Strait and in the vicinity of the Kuroshio. The latter studies result in three coauthored papers.

## **PUBLICATIONS**

S.-Y. Chao, P.-T. Shaw, M.-K. Hsu, and Y.-J. Yang (2006) Reflection and diffraction of internal solitary waves by a circular island, *Journal of Oceanography*, vol. 62, pp. 811-823, 2006. [published, refereed]

S.-Y. Chao, D.-S. Ko, R.-C. Lien and P.-T. Shaw (2007) Assessing the west ridge of Luzon Strait as an internal wave mediator, *Journal of Oceanography*. [in press, refereed]

Jan, S., C.-S. Chern, J. Wang and S.-Y. Chao, 2007: Generation of diurnal K1 internal tide in the Luzon Strait and its influence on surface tide in the South China Sea. *JGR*, vol. 112, C06019, doi:10.1029/2006JC004003. [published, refereed]

Wu, C.-R., S.-Y. Chao and C. Hsu, 2007: Transient, seasonal and interannual variability of the Taiwan Strait current. *J. Oceanography*, 63, 821-833. [published, refereed]

Y.-C. Hsin, C.-R. Wu, and P.-T. Shaw (2007) Spatial and Temporal Variations of the Kuroshio East of Taiwan: A numerical study, *Journal of Geophysical Research*. [submitted, refereed]